Astro 350

Lecture 40

Dec. 10, 2012

Announcements:

- Good news: now more homework!
- Bad news: Final Exam next Friday Dec 14, 8-11am here
  `www: Final Exam Info online`
- **ICES** available online – please do it!
  I do read and use comments!

Last time: formation of cosmic structure

Q: fate of a perfectly homogeneous universe?

Q: how inhomogeneous was our U when CMB released (recombination)?

Q: evolution of a single spherical overdensity? underdensity

Q: evolution of realistic universe?

if U perfect homogeneous initially
then every place identical to every other place
nowhere for galaxies to originate
$\rightarrow$ no "nucleation" sites

if U has one spherical uniform overdensity
evolves as "sub-universe" with $\Omega > 1$

- expands, but decelerates–"pulls away" from Hubble flow
- slows to a stop at max size
- then collapses, forms non-expanding bound object

real U begins with many tiny density fluctuations
high ρ behaves like spherical overdensity
amplified over time by gravity: **gravitational instability**
"the rich get richer and the poor get poorer"

The Birth of Structure: Setting the Stage

CMB "picture" of U at 400,000 years confirms
tiny density fluctuations everywhere, at all length scales
these formed the "seeds" of galaxies, stars, people today

during *radiation domination* (early U):

in early U, most mass/energy in hot photons and neutrinos (radiation)

expansion very rapid: too fast to overcome

density fluctuations barely grow

structure formation stalled

but as U expands, photons (and neutrinos!) redshift and lose energy since $E_\gamma \propto 1/\lambda \propto 1/a$

- radiation density drops faster than matter density

- at $t \approx 75,000$ years, *matter domination* begins

$\Rightarrow$ expansion slows, fluctuations can now grow!

$\Rightarrow$ structure formation begins!

Q: cosmic components? how will they evolve?

Structure Formation: Dark Matter

most cosmic matter is *dark matter*
weakly interacting $\rightarrow$ feels only gravity
(almost) no collisions $\rightarrow$ no pressure

once gravitational instability sets in
dark matter fluctuations begin to grow
galaxy "dark halos" form first!

the CMB gives a "snapshot" of
the initial pattern of density fluctuations
$\rightarrow$ random in space, but with definite patterns
in fluctuations: ripples on all length scales

Q: given this, where do we expect structures to form?

Structure Formation Theory: Predictions and Tests

Most cosmic matter is gathered into dark halos
and dark halos are where galaxies form
$\rightarrow$ galaxies themselves are much denser than the U on average
and thus galaxies mark regions where cosmic density was
initially higher than average
i.e., galaxies tell (roughly) where the initial "seeds" were

But: theories like inflation "sow the seeds" **randomly**
i.e., no way to predict whether a specific point (x, y, z)
will be an overdensity or underdensity

So: the mere presence of a galaxy neither verifies or
refutes our models
Q: how can we overcome this problem?

key idea:

density seed prediction for any point *is* random

but: overall **pattern** of density fluctuations

is not at all random, but specifically predicted

namely, can answer questions like this:

- *if* a galaxy found here,
  what is the *probability* of finding another galaxy 1Mpc away?
  i.e., what is the *pattern of clustering?*
- or can ask: what is the average "size" of a density fluctuation?
  technically: what is rms value of $(\rho - \rho_{\rm avg})^2 = \delta\rho^2$

In other words:

since the initial seeds are random

embrace this by adopting a *statistical* description

appropriate for finding patterns amidst randomness

fluctuations initially present on all length scales

Q: what does this mean? what would it look like?

Q: what does this imply for how structures form?
Hint: what are first objects to form, what happens afterwards?

Hierarchical Structure Formation

`www: movies! structure growth over cosmic time`

a "bottom-up" scenario
small structures form first

but fluctuations on all scales:
→ some groups of small structures are grouped together
as part of a larger overdensity

these first objects feel each other's gravity
merge to form larger structures
...which merge to form larger structures
∞ ...etc

`www: cluster formation`

dense regions connected by linear "filaments"

form knots in "cosmic web"

`www: cosmic web`

Q: how could we test if merging is how galaxies grow?

Evidence of Merging: Interacting Galaxies

Imagine galaxies today formed by merging
of smaller objects in past

Then several predictions:

- in past (=large distances, high redshift): expect to see fewer large/high-mass galaxies, more small/low-mass galaxies
- today: some galaxies should be "caught in the act" of merging
- our own Galaxy should show signs of past and ongoing merging

iClicker Poll: The Urge to Merge?

Which signatures of merging do we actually observe?

I. in past–fewer large/high-mass galaxies, more small/low-mass galaxies

II. today–some galaxies "caught in the act" of merging

III. Milky Way show signs of past and ongoing merging

A I only

B II only

C III only

D more than one of the above

E none of these are observed

Galaxy Merging Confirmed!

Evidence for "bottom-up" galaxy assembly is plentiful!

- distant = early Universe: more small galaxies
- galaxy mergers observed today
  `www: galaxy mergers`
- Milky Way observed to "cannibalize" dwarf galaxies
  `www: Sagittarius dwarf`
  `www: Magellanic clouds`

So far: only considered dark matter
but observable parts of galaxies are baryonic = stars+gas

Q: as structure formation begins, how will baryons and photons respond as dark matter structures begin to grow?